The Relationship of Erosion and Sediment Yield in a Yellow River Watershed System

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Abstract: Erosion and sediment yield data was evaluated from the Dalihe Watershed, an important branch of Yellow River. It was concluded that long-term erosion and sediment yield in the watershed system reached balance, and the sediment delivery ratio was approximate equal to I. However, as a result of short-term temporal variability from different rainfall events and annual rainfall trends, the sediment delivery ratio can reach more than 1 or less than 1 because the sediment transport in the watershed can be delayed or transported in subsequent by runoff erosion events. The sediment delivery ratio is closely correlated with runoff depth ratio, rainfall distribution, and the flood peak amplitude ratio in the watershed system. The spatial and temporal characteristics of the delivery ratio in watersheds at various scales and the factors that influence delivery ratio in the watershed systems are presented here. The relationship of erosion and sediment yield is illustrated and models based on the data are discussed in this paper.

Keywords: watershed, erosion, sediment yield, sediment delivery

1 Introduction

Since 1970, the mechanisms of sediment delivery and the relation of the sediment yield and erosion have gained importance in China. Gong et al., (1980) concluded that the average long-term sediment delivery ratio is approximately 1 in the hilly-gullied loess region of the Loess Plateau, regardless of the size of the watershed. Mu *et* al., (1982) stated that sediment hyper-concentration flooding is the major reason for a sediment delivery ratio of 1 in this district. Jing et al., (1997) studied the process of soil erosion based on geologic and geomorphology principles and analyzed the delivery ratio in different regions based on qualitative indices. For the past 10 years, Cai and Chen (1991) studied the relationship of erosion and sediment yield in a small watershed in the gullied-hilly loess region of the Loess Plateau. They concluded that erosion and sediment yield are in temporary disequilibria within individual years and rainfall events, and that the phenomenon of silt transport is variable in the short-term within the gully bed. Zhang *et al.*, (1994) also concluded that the delivery ratio is constant in the long-term within certain watersheds, and variable in the short-term. Although such opinions have been accepted, serious questions still exist regarding the characteristics of temporal-spatial changes of erosion and sediment yield, the role of runoff affecting sediment delivery ratio in watershed system, the hydraulic and landforms features for delivery ratio combined influence with interaction, and the different silt content flow influence on the delivery ratio. The research presented on these issues is revealing and has important theoretical and practical implications for exploring fundamental research questions on sediment sources within watershed systems, the mechanisms of soil erosion, transport, and deposition, and control methodologies for water and soil conservation.

2 Materials and Methods

The study region encompasses the total area of Wudinghe watershed. The area covers 30,260km^2 and can be divided into three distinct geologic types that include the tiverhead, the loess hilly-gullied area, and the desert melt wind erosion area. Each type covered 54.4%, 34.2% and 11.4% of the Wudinghe watershed area, respectively. The Dalihe River is a second level tributary of middle reaches of Yellow River and a first level tributary of Wudinghe River. It is located in the hilly-gullied district of loess plateau. The area is affected by typical continental monsoons during June to September and has an annual rainfall of approximately 450 mm. Annual erosion yield are approximately twenty thousands tons. The soils consist of thick loess deposits, which consist of a layer of Malan Loess overlying much thicker Lishi Loess (> 50 m). The watershed's physical conditions and geography are shown in Table 1.

Roehl's (1962) study has shown that upland erosion can been estimated by an erosion model or extrapolated from measurements on small plots, and are not equal to the sediment yield measured at the watershed outlet. To describe the differences, a sediment delivery ratio factor (Dr) has been developed:

$$Dr = Y/A$$

where Y is watershed sediment yield load and A is upland erosion load.

The gully watershed in small catchments in the loess area is the basic unit of erosion and sediment yield in which rhe character of vegetations, lands use, landforms and erosion types have obvious comparability (Wang, 1982; Cheng, 1988; Lei and Tang, 1995), including each type of erosion (splash, rill, shallow, gully erosion, and gravity erosion) (Cai, 1998). Based on the characteristics of soil erosion and sediment yield in loess hilly-gullied district, Mu et al., (1982) concluded that the small catchments unit (less than 1.0 km') is the sediment source in the Loess Plateau. The sediment delivery ratio was defined as the small catchments erosion modulus divided by the watersheds scale sediment yield modulus. For our research, the delivery ratio calculation is based on this definition.

Table 1 Physical conditions and geography of Dalihe River watershed system

River Systems		Observation Stations	Gully Type	Drainage Area (km")	Drainage Density (m/km')
Dalihe River	Chabagou River	Tuanshangou	Sublateral	0.18	
		Shejiagou	Branch	4.26	0.75
		Sanchuankou	Branch	21	0.79
		Xizhuang	Trunk	49	1.01
		Dujiagoucha	Trunk	96	1.06
		Caoping	Trunk	187	1.05
	Xiaolihe River	Lijiahe	Tributary of Dalihe	802	0.82
	Dalihe River	Suide	Outlet station of Dalihe	3,893	0.88

3 Results and discussion

3.1 Characteristics of temporal-spatial changes of the sediment delivery ratio

The average long-term sediment delivery ratio is approximately 1 in the watershed system, and peak values are reached in the $50km^2$—200 km' area watershed systems. Observation data for the Dalihe River watershed system are shown in Table 2. In watersheds with an area smaller than 50 km'-200 km', the measured sediment deposition is larger.

Table 3 shows that the sediment delivery ratio change is in the range of 0.1-18 in different years. The following conclusions were reached:

(1) Variations in the annual delivery ratio within a watershed system are related to variations of annual precipitation, annual runoff depth, and gully density. The annual delivery ratio is consistence with the long-term delivery ratio in watersheds ranging between $50km^2$—200 km^2. The soil erosion transport process in which inter-annual and intra-annual retained sediments or sediments retained at initial stage were re-eroded or transported again was observed. The normal year (1966) peak value interval is approximately that of the value of multi-year average. Following the peak value interval, a substantial amount of the silt is retained with increasing drainage area and the retained silt can make up 65 % of the erosion yield. A comparison of data from a dry year (1 965) and an abundant rain year (1966) reveals that following the peak value interval

the delivery ratio increases with the increase of drainage area, the magnitude is larger in low water years and smaller in high water years. The maximum annual sediment delivery ratio occurs in the dry year. In a comparison of intra-annual runoff depth and the amount of precipitation, especially for low water year vs. normal water years, smaller runoff and runoff depth has a greater delivery ratio. Therefore, changes in intra-annual sediment delivery ratio are not correlated with annual precipitation and annual runoff depth.

Table 2 Sediment delivery ratio averaged over years in Dalihe watershed system

Profile	Drainage area (/km^2)	Drainage density ([illegible] · km^{-2})	Annual average Runoff depth (/mm)	Sediment delivery ratio	Gully type
Tuanshangou	0.18			1	Sublateral
Shejiagou	4.26	0.78	55.6	0.83	Branch
Sanchuangou	21	0.19	52.3	0.75	Branch
Xizhuang	49	1.01	58.4	1.19	Trunk
Dujiagou	96.1	1.06	66.7	1.38	Trunk
Caoping	187	1.05	56.8	1.1	Trunk
Lijiahe	807	0.82	44.2	0.75	Tributary of Dalihe
Suide	3,893	0.88	50.2	0.89	Outlet station

Data covered years: 1961-1969; Drainage density from Mu, 1982.

Table 3 Sediment delivery ratio of different years in Dalihe watershed system

Profile	Annual average rainfall (mm)			Annual average runoff depth (mm)			Sediment delivery ratio		
	1965	1966	1967	1965	1966	1967	1965	1966	1967
Shejiagou	192.9	458.3	468.9	26.7	114.6	58.1	0.164	0.82	0.96
Sanchuangou	212.2	460.6	481.9	26.6	96	43.6	3.1	0.73	0.76
Xizhuang	209.2	484.3	502.7	28.1	145.6	55.3	7.77	I.32	1.59
Dujiagou	215.7	484.7	507.6	29.2	143.7	70.3	17.67	1.27	2.03
Caoping	213.5	472.9	503.2	27	117.4	59.2	9.81	0.99	1.54
Lijiahe	164	350.3	466	22.1	63.9	50.9	6.79	0.46	1.32
Suide	192.8	423.1	491.2	23.4	56		8.74	0.35	

(2) The annual delivery ratio is not correlated with total annual sediment discharge, and a larger delivery ratio is not correlated with greater sediment discharge. In the case of the Dujiacha River, in 1965 the sediment delivery ratio was 17.67, sediment yield was 36.51 X 10^4 t, whereas in 1966, the sediment delivery ration was 1.27, and the sediment yield reached 877.4 X 10^4 t.

(3) Changes in erosion induced sediment yield in a watershed are mainly related to several inter-annual rainstorm events. For eight runoff generated rainfall events in Tuanshangou in 1965, only one rainstorm event was recorded with flood observations at various profiles in Chabagou watershed. Sediment yield from a single rainstorm event only accounted for 23.9 % of the annual total amount. Inter-annual local runoff generation predomination is beneficial to silt retention, however, as during flood events there is a greater delivery ratio.

Table 4 shows that in single rainfall event and across different years, the erosion and sediment yield did not reach equilibrium. In contrast the average annual erosion and sediment yield across multiple years did reach equilibrium. Changes in the annual sediment delivery ratio of single rainstorm averaged across years to single rainstorm, as well as annual average sediment delivery ratio of various types of precipitation are correlated temporally and spatially. This shows that regardless of the changes in annual average or intra-annual delivery ratio, they are indicative of the flood sediment delivery ratio from a single rainstorm event.

Table 4 Spatial-temporal change characteristics of sediment delivery ratio for single rainstorm event or annual rainfall

Item		Shejiagou	Sanchuangou	Watershed Xizhuang	Dujiagou	Caoping
Maximum	Year	2.09	3.79	6.9	16.78	9.32
	Time	3.97	10.09	6.4	6.89	9.29
Mean	Year	0.82	0.78	0.9	1.18	1.00
	Time	0.84	0.88	1.1	1.21	0.88
Minimum	Year	0.16	0.46	0.3	0.40	0.53
	Time	0.17	0.09	0.1	0.14	0.06

3.2 Synthetic impact and interactions of geomorphic and fluvial dynamic characteristic indicators

Our analysis shows that based on the observation data shown in Table 2, a regression equation of synthetic impact of annual average runoff depth H (mm) and gully density G_m (km/km^2) in Dalihe River watershed system on annual average delivery ratio D_r can be given as:

$$D_r = 0.031 G_m^{1.08} H^{0.887} \qquad r = 0.985 \tag{1}$$

A forecast model of annual average sediment delivery ratio of different watershed scales in Dalihe River watershed system impacted by hydrologic and geomorphologic characteristics is:

$$D_r = 0657 A^{-0.014} G_m^{0.962} H^{0.152} \qquad r = 0.999 \tag{2}$$

where A is the drainage area (km’). In order to quantitatively analyze the impact and interactions of hydrologic and geomorphologic characteristics under modem geomorphologic conditions on sediment delivery ratio, an optimum binary orthogonal multinomial regressive equation was obtained based on multinomial regressive analysis on changes of characteristic values determined by equation (2) which was shown to be significant following a F test:

$$D_r = 0.0033 - 0.00128 H + 0.121 G_m + 0.0188 H G_m \tag{3}$$

The regression of variables in equation (3) all reaches a significant level of a = 0.01. F testing values of H, G_m and HG_m are 49,396, 43,103 and 1,428, respectively. The impact of H on D_r exceeded G_m, constituting an important factor that cannot be ignored in the long-term variability of the sediment delivery ratio.

3.3 Impact of a single rainstorm induced flood event

The measurement data show that the runoff depth quotient (H_b) in a watershed system related to a single rainstorm generated flood and magnitude of peak flood increase quotient (H_f) in gully system are closely related to pluviometric quotient (P_b) (Table 5). As a result of changes in rainfall induced sediment delivery ratio in Chabagou drainage system, runoff depth increases the quotient and peak flood increase magnitude (Fig. 1 and Fig.2). As $H_b > 1$, runoff per unit area in the gully systems increases, erosion capacity increases with increase of flow kinetic energy, and the sediment delivery ratio is greater than 1. As $H_b > 1$, the per unit area runoff capacity decreases in the drainage system, the increase in runoff loss due to infiltration and decay of kinetic energy is increases silt retention, and the sediment delivery rate is smaller than 1. When $H_b \approx 1$ and rainfall is evenly distributed, erosion and sediment yield are liable to reach balance. Therefore, the increase ratio of a single rainfall induced runoff depth serves as per unit area flow kinetic energy characteristic indicator for determining whether erosion in watersheds of varying grades can reach balance with the sediment yield. Figure 2 shows that the relationship of D_r and H_b under the same rainstorm conditions in Lijiahe and Qingyangcha, and the two trunk gullies of Dalihe River, and Suide and Tuanshangou of the Wudinghe River. There is a significant correlation between H_b and D_r in watersheds of varying scales.

Table 5 Relations between H_b and H_f with P_b

Profile	Equation	Correlative coefficient (/r)	No. of sample (/n)
Shejiagou	$H_b=1/(1.89-1.09P_b)$	0.655	31
	$H_f=P_b/(0.179-0.109P_b)$	0.699	
Sanchuangou	$H_b=1/(1.086-0.344P_b)$	0.715	25
	$H_f=1/(0.037-0.01P_b)$	0.713	
Xizhuang	$H_b=P_b/(1.37-0.616P_b)$	0.853	18
	$H_f=P_b/(1.345-0.216P_b)$	0.971	
Dujiagou	$H_b=P_b/(0.511-0.015P_b)$	0.631	20
	$H_f=P_b/(0.01-0.001P_b)$	0.619	
Suide	$H_b=P_b/(0.907-0.342P_b)$	0.698	29
	$H_f=1/(0.019-0.012P_b)$	0.728	

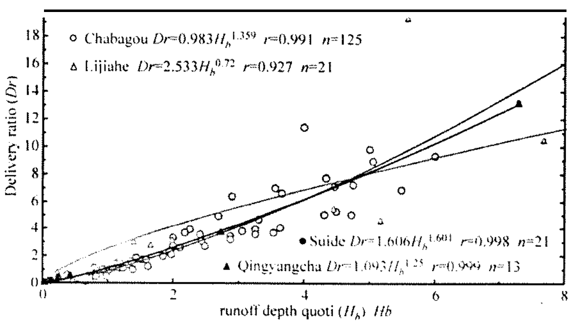

Fig. 1 Relationship between runoff depth quotient (H_b) and delivery ratio (D_r) for a single rainfall

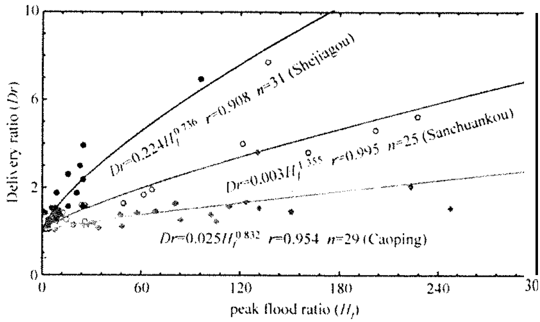

Fig. 2 Relationship between delivery ratio D_r and change magnitude of peak flood ratio H_f

There is an increase in the magnitude ratio of a single rainfall induced peak flood in the Chabagou drainage system (Fig.3). The sediment delivery ratio increases with the increase of peak flood increase magnitude quotient, when H_f is greater than a certain value. A threshold value of H_f impacting erosion and sediment yield balance also exists. Under conditions with the same sediment delivery ratio, the larger the watershed will have a greater increase in the magnitude quotient. When the delivery ratio is equal to 1, a threshold of peak flood increase quotient can be reached (i.e., the Shejiagou is approximately 10, the

Sanchuankou increases to approximately 30, and the Caoping increases to approximately 80). When the above-mentioned peak flood increase quotient in the drainage system reaches threshold, equilibrium is reached between erosion and sediment yield. When the delivery ratio is 1, deposition occurs when the threshold is small, and scouring occurs when the threshold is greater. The larger the drainage area, the smaller the rates of increasing peak flood magnitude.

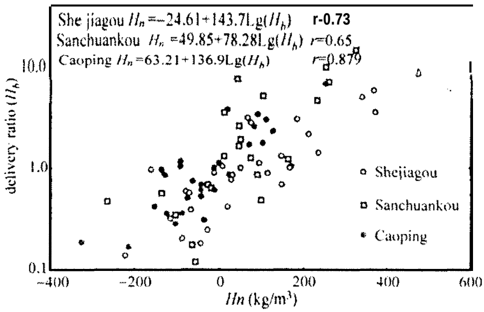

Fig. 3 Relationship between runoff depth H_b and silt content increment H_n

Of the 8 runoff events generating from rainfall in 1965 in Tuanshangou, only one event resulted in flooding on all profiles in Chabagou. A single event rainstorm yielded sediment volume that accounted for 23.9 % of the year's total sediment. The remaining 7 rainfall events generated runoff locally which clearly reflected the changes in erosion and sediment yield in 1965 at the Wangjiagou station, where the delivery ratio was only 0.164. Based on regressive analysis, it is possible to build a prediction model that described the impact of the rainfall-generated runoff in the Chabago drainage system of the Dalihe River in the loess hilly-gully areas on sediment delivery ratio:

$$D_r = 0.403 P_b^{0.37} H_b^{1.066} H_f^{0.191} \quad r = 0.996 \ n = 125 \tag{4}$$

The transformation relationship of a single rainfall related sediment delivery ratio with erosion amount and sediment yield could be given in the following expression:

$$T = Y / D_r \tag{5}$$

where T is the single rainfall induced sediment delivery ratio, Y is the amount of erosion, and D_r is to sediment yield.

3.4 Impact of flow silt carrying capacity

Under single rainfall events, the silt-carrying capacity in different grade drainages can be described by the equation below:

$$H_n = H_{so} - His \tag{6}$$

where H_n denotes per unit runoff volume increment of silt yield (kg/m^3); H_{so} is the average silt content delivered from various grades of gullies (kg/m^3); and H_{si} is the average silt content delivered from small unit gully drainage (kg/m^3). Measurement data show that changes in silt-laden capacity of gully runoff are

Table 6 Equations indicating relationship between runoff depth H_b and silt content increment H_n

Station	Equation	Correlative coefficient (/r)	No. of sample (/n)
Shejiagou	H_n=-25.71+92.8lgD_r	0.76	31
Sanchuankou	H_n=29.58+67.01gD_r	0.688	23
Xizhuang	H_n=61.002+122.1lgD_r	0.73	19
Dujiagou	H_n=61.7+93.59lgD_r	0.777	20
Caoping	H_n=58.64+114.89lgD_r	0.917	30

similar to the runoff increase or decrease per unit area (Fig.3). Therefore, the sediment delivery ratio of the drainage system is similar to the rise or fall of silt-laden capacity of the gullies, and the scouring and siltation of the gully beds (Table 6). When the kinetic energy of silt-laden runoff increases, both silt carrying capacity and silt yield increases, hence the sediment delivery ratio is greater than 1. When the silt carrying capacity in these drainage systems is equal to that of unit small catchments, the delivery ratio is 0. When the kinetic energy weakens, silt is deposited, and delivery ratio is smaller than 1.

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